

NASA Technical Memorandum 105806

Relative Sliding Durability of Candidate High Temperature Fiber Seal Materials

Christopher DellaCorte and Bruce M. Steinetz
Lewis Research Center
Cleveland, Ohio

August 1992



RELATIVE SLIDING DURABILITY OF CANDIDATE HIGH TEMPERATURE FIBER SEAL MATERIALS

C. DellaCorte and B.M. Steinetz
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

This paper reviews and compares the relative sliding durability behavior of six candidate ceramic fibers for high temperature sliding seal applications which has been previously reported by the authors in several separate publications as part of an ongoing research program. Pin on disk tests were used to evaluate potential seal materials by sliding a tow or bundle of the candidate ceramic fiber against a superalloy test disk. Tests were conducted in air under a 2.65 N load, at a sliding velocity of 0.025 m/sec and at temperatures from 25 to 900 °C. Friction was measured during the tests and fiber wear, indicated by the extent of fibers broken in the tow or bundle, was measured at the end of each test.

For most of the fibers, friction and wear increase with test temperature. The relative fiber durability ranking correlates with tensile strength indicating that tensile data, which is more readily available than sliding durability data, may be useful in predicting fiber wear behavior under various conditions.

A dimensional analysis of the wear data shows that the fiber durability is related to a dimensionless durability ratio which represents the ratio of the fiber strength to the fiber stresses imposed by sliding. The analysis is applicable to fibers with similar diameters and elastic moduli.

Based upon the results of the research program, three fiber candidates are recommended for further study as potential seal materials. They are a silicon based complex carbide-oxide fiber, an alumina-boria-silica fiber and an aluminosilicate fiber.

INTRODUCTION

A research program is underway at NASA Lewis Research Center to develop advanced high temperature sealing technology for hypersonic vehicles. Sliding seals are needed to meet the needs of advanced propulsion systems such as the new generation of launch vehicles and especially hypersonic vehicles such as NASP, illustrated in figure 1. In these applications, engine and airframe components must be sealed from hot engine combustion gases and the frictional heat of the atmosphere to prevent damage (ref. 1).

Material evaluation is a key technology area for seal development. Several proposed hypersonic vehicles will, for example, require sliding seals to operate in adverse environments encountered in engines and on control surfaces such as flaps and elevons. It has been estimated that linear sliding seals must operate successfully at temperatures near 1000 °C (ref. 3).

One current approach to address some of these advanced sealing problems is to use a braided linear rope seal in sliding contact with an actively cooled metallic counterface (ref. 3). The rope seal is woven

from ceramic fibers and is required to be able to withstand high temperature, oxidative and reducing environments which may contain water vapor. Figure 2 shows, schematically, one such rope seal design.

For long seal life and low seal actuation forces, friction and wear of the rope must be minimized. Recent research suggests that, in sliding contacts, unlubricated ceramics exhibit high friction and wear properties (ref. 4). Therefore, the determination and understanding of high temperature friction and wear properties of candidate seal materials are important issues.

This paper reviews recent research addressing these issues. In this paper, the durability behavior of six candidate ceramic fiber materials which have been tested and reported in references 5 to 7 are reviewed and compared. The goal of the paper is twofold. One goal is to compare the relative durability of these ceramic candidate materials and assess their potential for seal use. The second goal is to identify two or three of the most promising fiber candidates for further consideration as seal materials.

MATERIALS

The materials tested were one counterface material, Inconel 718 and six fiber materials (three of which, Nextel 312, 440, and 550 were tested in an as received and also heat treated condition giving a total of nine fiber specimen types tested). The fibers tested were: the 3M company's Nextel 312 and Nextel 440 alumina-boria-silicate fibers; Nextel 550 alumina-silicate fiber; Nextel 610 alumina fiber; UBE/Textron's Tyranno and Dow Corning's HPZ both of which are silicon based complex carbide-oxide fibers. The fibers' compositions and mechanical properties are given in table I. Details pertaining to each fibers structure and chemistry can be found in references 5 to 7.

The Nextel 312, 440, and 550 fibers tested, were slightly oval in cross section with diameters of about 11 μm . The Tyranno, HPZ and Nextel 610 were approximately circular in cross section and were 11, 12.6, and 10.5 μm in diameter respectively.

Fiber Treatments

All of the samples were heat cleaned at 500 °C, in air for 1 hr to remove an organic sizing compound used by the manufacturer during processing (ref. 8). Furthermore, some samples of the Nextel 312, 440, and 550 which are designated with an HT suffix, Nextel 440HT for example, were heat treated in air at 950 °C for 12 hr to make the fibers more resistant to moisture degradation at elevated temperature. In general, this heat treatment slightly lowers the tensile strength of the fibers (ref. 8).

Fiber Selection Rationale

Alumina-boria-silica.—Nextel 312 and 440 are alumina-boria-silica ceramic fiber materials which were selected because of their high degree of formability and good high temperature properties. These fibers are commercially available in fiber or woven form and are considered "standards" in the field of ceramic fibers. This fiber chemistry was studied previously (refs. 9 and 10) and found to display good friction and wear properties making Nextel 312 and 440 viable sliding seal candidates. One weakness of this fiber system is the boria content. Nextel 312 contains 14 wt% of the glass former, boria, while Nextel 440 contains only 2 wt% boria. Nextel 312, therefore, is more amorphous and glasslike and also has, in

general, lower tensile strength than Nextel 440. Boria, B_2O_3 acts as a glass forming additive and tends to make the fibers chemically reactive (ref. 9) creating the potential for fiber strength reduction. For this reason, the manufacturer, 3M, developed Nextel 550 an alumina-silica fiber which does not contain boria.

Alumina-silica.—Nextel 550 has mechanical properties similar to Nextel 440 but only contains alumina (73 wt%) and silica (27 wt%) and does not suffer the same type of chemical vulnerability as boria containing compositions. For this reason it is believed to have better high temperature strength stability making it an excellent candidate for sliding seal applications.

Alumina.—Nextel 610 is an alumina, Al_2O_3 , fiber. It has excellent high temperature strength and chemical stability and is, therefore, an excellent seal fiber candidate. The elastic modulus for alumina, however, is twice that of the other fibers tested in this program. This makes the alumina substantially less flexible and may make it difficult to weave it into complex seal architectures and the reduced flexibility may affect durability.

Si-O-C-N(Ti).—Both Tyranno (Si-O-C-Ti) and HPZ (Si-O-C-N) have complex carbide oxide compositions and exhibit excellent high temperature strength properties. Furthermore, fiber cross sections of these fibers tend to be more circular than oval (like the Nextel 312 and 440 fibers) and thus may exhibit better leakage properties when woven into seals making them promising seal fiber candidates. Since these fibers are not, strictly speaking, oxide fibers they do form an oxide layer on their surface when heated in air and this may affect their tribological performance.

Counterface material.—The counterface test disks were made of Inconel 718, a nickel-chromium alloy precipitation hardened to 34 on the Rockwell C scale. Table II gives the composition and some representative properties of the disk material. This material is being considered as a possible candidate for seal applications because of its high temperature strength and oxidation resistance.

Prior to testing, the disk surface is lapped with alumina abrasive to a surface finish of about $0.1 \mu m$ rms. Some specimens were diamond ground to a surface finish of about $0.7 \mu m$ rms to ascertain the effect of counterface roughness on fiber durability. After lapping (or grinding), the specimens were cleaned with freon, ethyl alcohol, scrubbed with a paste of levigated alumina and deionized water, rinsed with deionized water and air dried.

APPARATUS AND PROCEDURES

The candidate fiber durability was measured using a pin on disk type test. With this apparatus, the wear characteristics of the fibers are obtained by sliding a small sample bundle of fibers against the flat face of a rotating disk in a friction and wear rig. Friction is measured continuously during the test and fiber wear is measured at the end of each test which typically lasted for 2 hr. Since many newly developed ceramic fibers are only available in limited quantities this technique is advantageous because it requires a minimum of material and minimal specimen preparation yet simulates the anticipated seal application.

This testing approach is a variation of the author's work done previously on woven ceramic fabric materials (refs. 9 and 10). In that work, samples of woven ceramic fabric to be tested were draped over the tip of a hemispherically tipped pin and rubbed against metal and ceramic test disks. The approach was successful but required a substantial amount of woven fabric for each sample.

The technique used to study the fiber candidates eliminates the need for woven fiber samples by using a short tow or bundle of fibers which is draped over the tip of a specially machined Inconel 718 pin. The bundle is held in place with loops of circumferentially wound stainless steel wire (see fig. 3). The pin has grooves machined into the tip and shank to accept the fiber strand and prevent its slippage during testing.

As in the previous work with the woven fabric (refs. 9 and 10), the pin has a small flat spot at its tip, 3.2 mm in diameter, to better support the fiber bundle and provide a uniform sliding area. The bundle is given a one-half or 180° twist across the flat contact spot to help contain the bundle in the sliding contact and to orient the fibers at ~45° angle with the sliding direction to better simulate proposed braided seal configurations (see fig. 4).

To test a fiber candidate, a bundle of fibers, usually containing about 6000, 11 μ m diameter fibers, is mounted on the pin specimen. The pin is then slid against a counterface disk in a high temperature pin on disk tribometer. The disk is 63.5 mm in diameter and 12.7 mm thick. The pin generates a 51 mm wear track on the disk.

Figure 5 shows a schematic of the tribometer used in this work. The tribometer has been described in detail elsewhere (ref. 11) and its main features will only be briefly described here.

The pin on disk tribometer is capable of sliding pin and disk specimens at loads from 0.1 to 100 kg at sliding speeds from 0.025 to 22 m/sec. The specimens can be heated using a SiC glowbar furnace to temperatures of 1200 °C. For the tests conducted here, the sliding speed was 0.025 m/sec and the load was 0.270 kg (2.65 N). The test atmosphere was ambient air with a relative humidity ranging from 50 to 75 percent at 25 °C. Test temperature was 25, 500, and 900 °C. The test duration was 120 min. Friction was continuously measured during the tests. Wear was qualitatively monitored during the tests using an LVDT position sensor on the pin specimen and more exactly quantified after each test.

By monitoring pin movement during the test, excessive fiber breakage can be detected and sliding can be suspended prior to the end of the typical 2 hr test period. Preliminary tests indicated that fiber wear occurs in a fairly uniform manner during the tests. Fiber wear data, within an uncertainty of about 5 percent, was determined using SEM micrographs and from post test visual observations.

RESULTS

The friction and wear results for the tests conducted are given in table III and figure 6. Wear resistance is given by cycles to failure, CTF which is a common durability parameter for fiber materials (ref. 12). For these tests, the CTF is determined by first dividing the number of cycles tested by the number of fibers broken during the test and then multiplying by the total number of fibers in the bundle tested (in our case there are usually 6000 fibers). For example, if 50 percent of the fibers in a bundle (3000 fibers) break after a 2 hr test (1200 revolutions or cycles) the CTF is $(1200) \cdot (6000/3000) = 2400$. That is to say it would take 2400 disk revolutions or cycles to break through the entire 6000 fiber bundle.

This measurement assumes that the fiber breakage rate is linear with time and is, therefore, simplistic. However, CTF is a standard measure for fiber durability in the textile industry and proves to be a useful measurement for these tests.

The friction and durability data is given in table III and a typical friction plot is given in figure 7. Each data curve in this plot represents the average of at least three experiments. The data scatter values are shown in table III. The following sections below discuss the results for each type of fiber material.

Alumina-Boria-Silica

In terms of friction, both the Nextel 312 and 440 were similar. At room temperature the friction coefficient was about 0.55 and it increased to about 0.7 at elevated temperatures. In terms of fiber durability, however, there were significant differences between the two fibers and between the heat treated and non heat treated fibers.

The durability, or CTF, was higher for the non heat treated fibers, and Nextel 440 was more durable than Nextel 312. At elevated temperatures, Nextel 312 in both conditions had very little durability dropping to less than 200 cycles at 900 °C. Nextel 440 performed better than the Nextel 312 and in the non heat treated condition retained significant durability even at 900 °C. In the heat treated condition, Nextel 440 lost much of its durability at 900 °C.

Alumina-Silica

The aluminosilicate fiber, Nextel 550, performed similarly to the Nextel 440 in the non heat treated condition in terms of durability. The friction coefficient for the Nextel 550 at 500 °C was 0.36 which was significantly lower than for the Nextel 440 which was about 0.65 to 0.80. This may be due to the differences in fiber chemistry.

Alumina

The alumina fibers displayed good friction and durability. The friction coefficient was highest at room temperature, 0.51, and decreased at elevated temperatures to about 0.30. This is in excellent agreement with results reported by Sliney and Deadmore for monolithic alumina rub blocks sliding against Inconel 718 (ref. 13). In their work, they attributed the decrease in friction to the formation of a lubricious oxide film at the sliding interface which reduced friction and wear. For the alumina fibers, the durability at elevated temperatures is also better than at room temperature indicating that the oxide film which formed reduces wear as well as friction. One drawback of the alumina fibers, however, is their stiffness. Since the elastic modulus for alumina is almost twice that of the other fibers tested they are very stiff and difficult to handle.

Si-O-C-N(Ti)

The Tyranno fibers (Si, O, C, Ti) displayed very low friction and remarkably low wear at room temperature. This may be attributed to Tyranno's high strength and its unique chemical composition. At elevated temperatures, however, friction and wear increased considerably. In addition, post test microscopy of the fibers indicated that some oxidation/chemical reaction of the fibers had occurred (ref. 6). This may be a reason for the increased friction and wear at elevated temperatures.

The HPZ fiber (Si, O, C, N) showed a similar oxidation/chemical reaction surface morphology (ref. 6) after testing but its properties were quite constant over the entire temperature range. Friction was relatively high, but stable, ranging from 0.59 at 500 °C to 0.69 at room temperature. Fiber durability was also nearly constant at about 2070 ± 450 CTF from 25 to 900 °C. These properties are not the best in terms of friction and durability. For example, Nextel 550 displays lower wear (better durability) at all temperatures compared to the HPZ fiber. However, HPZ's uniform properties are very desirable from an engineering design point of view.

DISCUSSION

Fiber Ranking

The purpose of these tests is to determine the relative durability of the six candidate fibers and to select two or three of the most promising fibers for further consideration as seal materials. In addition, this work serves as an evaluation of the screening technique from which the data can be used to gain a better understanding of the important factors affecting fiber durability and friction.

The relative durability of the fibers can be seen by examining the cycles to failure data (see table III). Based upon these findings, Nextel 550 and 440, in the unheat treated condition, have nearly equivalent durability properties. In terms of friction, Nextel 550 has lower friction at 500 °C than Nextel 440. In addition, when the alumina-boria-silicate fibers (Nextel 440 and 312) are heat treated their durability is reduced. Nextel 550 did not suffer significant strength degradation after the thermal treatment. Therefore, Nextel 550 is a leading candidate for future seal material consideration followed by Nextel 440 in the unheat treated condition. Since HPZ exhibits very stable friction and durability properties over the entire temperature range it is also a desirable candidate from an engineering design point of view.

To better understand the reason(s) for this ranking it is important to consider the surface features of the worn specimens and then combine those observations with the fibers' mechanical and physical properties. This work has been reported on earlier (refs. 5 to 7) and these results will be highlighted along with other findings in order to arrive at material choice recommendations for further consideration.

POST TEST MICROSCOPIC ANALYSES

Much can be learned about tribological tests by examining the wear surfaces after testing. There is a marked difference in appearance between the oxide fiber and complex carbide-oxide fiber surfaces after sliding. This difference primarily shows up after elevated temperature testing during which the non-oxide fibers oxidize and the oxide product seems to play a significant role in the tribological behavior. This is in contrast to the oxide fibers which exhibit brittle fracture tribological behavior over the entire test temperature range.

Figures 8 to 10 show SEM photomicrographs of fiber bundles of the oxide fibers Nextel 440 and 312 after sliding against the Inconel 718 counterface disk. One apparent aspect is that the fiber bundles are wearing by brittle fracture and not by gentle abrasion. This finding is consistent with work done previously (refs. 9 and 10). Also noted is that little debris, transferred disk material or reaction products

seem to be present (ref. 7). This is consistent with the fact that the Nextel 312 and 440 fibers tested are oxide ceramics which would not normally react in an air environment at these modest test temperatures.

Figures 11 and 12 show the surface features of the complex carbide-oxide fibers (HPZ and Tyranno) after the sliding tests. The specimens from room temperature tests look very similar to the oxide fiber test specimens. That is, they are wearing in a brittle manner. After testing at elevated temperature, however, significant fiber oxidation occurs and forms a wear debris deposit at the sliding interface which affects friction and durability. This type of behavior indicates that the naturally formed passivating oxide layer is easily worn off due to the sliding action and exposes new fiber surface which readily oxidizes leading to increased wear (ref. 6). This type of wear may be detrimental to sealing properties and long term stability of a braided seal and must be taken into consideration when making seal material selections.

Friction: Relation to Fiber Chemistry

The friction coefficients measured for the fibers studied here are similar to values measured in previous work by this author (refs. 9 and 10) and by others working with unlubricated ceramic sliding (refs. 4, 14, and 15). For the alumina-boria-silicate fiber chemistry (Nextel 440 and 312) the friction at room temperature is about 0.5 and it increases slightly to about 0.7 at elevated temperatures where the counterface oxidizes. This is in general agreement with the trends measured for the same fibers tested in woven fabric form (ref. 10).

For the alumina-silicate fiber, Nextel 550, the friction drops to 0.36 at 500 °C perhaps due to the growth of a low shear strength oxide film at the sliding interface. At 900 °C, however, further surface oxidation of the disk and possible interaction of the metal oxides from the disk and the fibers cause an increase in friction to about 0.6.

It is interesting to note that for the pure alumina fiber, Nextel 610, the friction coefficient decreases with temperature to about 0.3 at 500 and 900 °C. These values are in very good agreement with values for Inconel 718 sliding against pure alumina reported by Sliney and Deadmore (ref. 13) using a rub block on ring apparatus. Therefore it seems that the test configuration used here for the fibers gives equivalent friction results to more standardized tests for the same fiber/counterface chemistry. This agreement enhances the confidence in the friction data.

Durability: Relation to Fiber Properties

Table IV shows the tensile strength as a function of temperature for the fiber conditions tested. From the data in tables III and IV, it can be seen that the ranking of the fibers in terms of tensile strength is similar to the ranking of the fibers in terms of CTF or durability. Although the correlation of the rankings of the fiber durability and tensile strength is good, a mathematical or functional relationship between CTF and tensile strength is not immediately apparent.

To better understand the factors affecting fiber durability, a dimensional analysis of the fiber durability for the two Nextel fibers 312 and 440 was conducted taking into account mechanical factors which are likely to affect durability such as tensile strength, load, and friction coefficient. These fibers were chosen for dimensional study because their oxide chemistry made it likely that predominantly mechanical

properties control durability. Furthermore, these fibers have been well characterized and mechanical property data such as tensile strength is readily available and can be used as input to check the results of the dimensional analysis. The dimensional analysis is described in detail in reference 5 and only the highlights will be reviewed here.

The dimensional analysis conducted to determine the important test and material parameters on fiber durability resulted in the discovery of a durability parameter or ratio. The durability ratio is defined as the ratio of the fiber strength in tension (tensile strength \cdot fiber diameter² e.g., O^2) divided by the sliding friction force (friction coefficient-applied normal load), or, $(TS \cdot D^2)/(\mu \cdot F_n)$.

The relationship established by the dimensional analysis and the identification of an important dimensionless parameter helps to explain and understand the data. The usefulness of the analysis and the dimensionless durability ratio can be seen by examining a plot of fiber durability (CTF) versus the durability ratio for the Nextel 312 and 440 as shown in figure 13. Though the data is not comprehensive, a trend is apparent. That is that, rather than a simple linear function, the CTF seems to be a step function of fiber strength to fiber breakage forces. Others have found similar connections between ceramic wear and fracture behavior (ref. 13).

The CTF is low for $(TS \cdot D^2/\mu F_n)$ ratios lower than about 0.12. Above this point the CTF rises dramatically. This implies that a threshold exists around a ratio of 0.12 below which poor fiber durability is exhibited and above which good fiber durability is observed.

Much of the data scatter in figure 13 may be the result of uncertainties in the tensile strength data which in some cases was extrapolated from data at other temperatures and also friction data scatter. Nonetheless the dimensional analysis helps to delineate the important variables and helps to explain the data we measure.

For example, the analysis shows why the fibers with higher tensile strength exhibit more durability. Also, the gain in strength must be tempered by a possible increase in friction or load which cause the frictional stresses on the fibers to increase. This indicates that durability may be enhanced by reducing the loads or by lubricating the fibers. Both of the options are available to seal designers and have been shown to be effective in previous research with these materials in woven fabric form (refs. 9 and 10).

Although the data scatter is large, figure 13 can be used to determine the approximate value of the threshold separating durability behavior for this materials system. Since this analysis is based upon mechanics and data taken from tests where physical properties seem to dominate durability behavior, it is expected that the durability ratio will be important only for other materials and test conditions that do not experience significant chemical activity during testing such as other oxide materials like Nextel 550 and 610.

When data for these other oxide fiber systems is plotted with the Nextel 312 and 440 data using the durability ratio as in figure 14 it is seen that the agreement of the Nextel 550 data with the data for the alumina-boria-silicate is reasonably good. The agreement for the alumina fiber, Nextel 610, however, is poor. This may be due to the difference in the elastic moduli between the Nextel 610 and all of the other fibers tested. The modulus for the Nextel 610 is about twice that of the other fibers tested making it much stiffer and this may have a significant effect on the durability. These observations indicate that mechanical properties have a major impact on the fiber durability and hence may affect seal durability as well.

Further work is needed to understand the relationship between stiffness and durability. From these results, it seems that the fiber stiffness, which is related to the elastic modulus and the fiber diameter, must be approximately equal in order to make comparisons between different fibers using the simple dimensionless analysis.

For the complex carbide-oxides, HPZ and Tyranno, chemical reactivity (oxidation) with the atmosphere and other materials in the environment in addition to mechanical effects may have a significant impact on durability at elevated temperatures. Thus the mechanical model will probably only apply at low temperatures. The data for HPZ and Tyranno are plotted along with the Nextel data in figure 15. There is good agreement with the dimensional analysis model at room temperature which is expected since these complex carbide-oxide fibers behave in a brittle manner at low temperatures. At elevated temperatures, the data deviates from the model indicating that chemical effects, namely fiber oxidation, and mechanical effects may be playing a role in durability.

CONCLUSIONS

The relative durability of six fiber materials was evaluated using a pin-on-disk tribometer. The test technique developed provided repeatable data in a convenient manner using a minimal amount of test material.

1. The test results helped to identify three of the six fibers which should be considered for further study. They are Nextel 440 ($\text{Al}_2\text{O}_3\text{-SiO}_2\text{-B}_2\text{O}_3$) in the non heat treated condition, Nextel 550 ($\text{Al}_2\text{O}_3\text{-SiO}_2$) and HPZ (Si-O-N-C).
2. The fiber durability ranking correlates well with the tensile strength ranking indicating that tensile data may provide insight for seal material selection and screening.
3. In general, fiber durability decreased and friction increased with temperature. This may be due to a variety of factors including lower fiber strength and possible changes in the chemistry of the fiber/counterface sliding contact e.g., due to oxidation.
4. A simple dimensional analysis indicates that fiber durability is related to a durability ratio of the fiber strength to the frictional stresses imposed on the fibers due to sliding. This analysis is useful where mechanical properties dominate durability as is the case for oxide fibers and for complex carbide-oxide fibers tested at room temperature.
5. Fibers that had high elastic modulus, such as Alumina (Nextel 610) were much stiffer than the other fibers tested and were difficult to handle due to their decreased flexibility. Although the durability was good, the high stiffness may preclude its consideration as a seal candidate materials.

ACKNOWLEDGMENTS

The author would like to thank Mr. V. Lukaszewicz for preparing the fiber specimens and for conducting the fiber durability tests. Also, the SEM analyses by Mr. A. Korenyi-Both are appreciated.

REFERENCES

1. Steinetz, B.M.; DellaCorte, C.; and Sirocky, P.: On the Development of Hypersonic Engine Seals. NASA TP-2854, 1988.

2. Stephens, J.R.: HITEMP Program Overview. HITEMP Review 1990: Advanced High Temperature Engine Materials Technology Program. NASA CP-10051, 1990, pp. 1-23.
3. Steinetz, B.M.; DellaCorte, C.; and Tong, M.: Seal Concept and Material Performance Evaluation For the NASP Engine. Structures 1989, NASA CP-7045, Vol. 6, 1989, pp. 39-58.
4. Yust, C.S.; and Allard, J.F.: Wear Characteristics of an Alumina Silicon Carbide Whisker Composite at Temperatures to 800 °C in Air. STLE Tribol. Trans., vol. 32, July 1989, pp. 331-338.
5. DellaCorte, C.; and Steinetz, B.M.: Relative Sliding Durability of Two Candidate High Temperature Oxide Fiber Seal Materials. NASA TM-105199, 1991.
6. DellaCorte, C.; and Steinetz B.M.: Sliding Durability of two Complex Carbide-Oxide Candidate High Temperature Fiber Seal Materials in Air to 900 °C. NASA TM-105554, 1992.
7. DellaCorte, C.; and Steinetz, B.M.: Tribological Evaluation of an $\text{Al}_2\text{O}_3\text{-SiO}_2$ Ceramic Fiber Candidate for High Temperature Sliding Seals. NASA TM-1056611, 1992.
8. Holtz, A.R.; and Grether, M.F.: High Temperature Properties of Three Nextel Ceramic Fibers. Advanced Materials Technology 1987: 32nd International SAMPE Symposium and Exhibition, R. Carson, ed., SAMPES, Covina, CA 1987, pp. 245-256.
9. DellaCorte, C.: Tribological Properties of Alumina-Boria-Silicate Fabric From 25 to 850 °C. STLE Tribol. Trans., vol. 32, July 1989, pp. 325-330.
10. DellaCorte, C.; Steinetz, B.M.; and Brindley, P.K.: Tribological Properties of Ceramic/ $\text{Ti}_3\text{Al-Nb}$ Sliding Couples for Use as Candidate Seal Materials to 700 °C. NASA TM-102401, 1990.
11. Sliney, H.E.; and DellaCorte, C.: A New High Test Machine for Measuring Friction and Wear in Controlled Atmospheres to 1200 °C. Lubr. Eng., vol. 47, no. 4, Apr. 1991, pp. 314-319.
12. Miller, B.; Friedman, H.L.; and Turner, R.: Design and Use of a Cyclic Tensile Abrader for Filaments and Yarns-A Study of Polyester Monofilament Wear. Tex. Res. J., vol. 53, no. 12, Dec. 1983, pp. 733-740.
13. Sliney, H.E.; and Deadmore, D.E.: Friction and Wear of Oxide-Ceramic Sliding Against IN-718 Nickel Base Alloy at 25 to 800 °C in Atmospheric Air. NASA TM-102291, 1989.
14. Kear, B.H., ed.: Tribology of Ceramics. National Academy Press, 1988, pp. 1-12.
15. Boch, P.; Platon F.; and Kapelski, G.: Effect of Temperature and Environment on Wear and Friction of Al_2O_3 and SiC Ceramics. Proceedings of the Fifth International Congress on Tribology, Vol. 1, K. Holmberg and I. Nieminen, eds., Finnish Society for Tribology, Helsinki, Finland, 1989, pp. 114-119.

TABLE I.—COMPOSITION AND SELECTED PROPERTIES OF
FIBERS TESTED (MANUFACTURERS DATA)

Fiber material	Manufacturer	Composition, wt%	Diameter, μm	E, GPa
Nextel 312	3M ↓	$62\text{Al}_2\text{O}_3\text{-}24\text{SiO}_2\text{-}14\text{B}_2\text{O}_3$	11	150
Nextel 312HT		$62\text{Al}_2\text{O}_3\text{-}24\text{SiO}_2\text{-}14\text{B}_2\text{O}_3$	↓	150
Netel 440		$70\text{Al}_2\text{O}_3\text{-}28\text{SiO}_2\text{-}2\text{B}_2\text{O}_3$		190
Nextel 440 HT		$70\text{Al}_2\text{O}_3\text{-}28\text{SiO}_2\text{-}2\text{B}_2\text{O}_3$		↓
Nextel 550		$73\text{Al}_2\text{O}_3\text{-}27\text{SiO}_2$		
Nextel 550HT		$73\text{Al}_2\text{O}_3\text{-}27\text{SiO}_2$	↓	↓
Nextel 610	UBE/Textron Dow Corning	Al_2O_3	10.5	366
Tyranno		50Si 30C 170 3Ti	11	180
HPZ		57Si 28N 10C 50	12.6	176

TABLE II.—COMPOSITION AND HARDNESS OF
INCONEL TEST DISK SPECIMENS

Property	Value
Composition, wt%	70Ni, 16Cr, 7.5Fe, 2.5Ti, 1Al, 1Co, 1Mn, 0.1C, and 0.9 other
Hardness, Rockwell C	RC34

TABLE III.—FRICTION AND DURABILITY DATA SUMMARY

Fiber material	Composition, wt%	Diameter, μm	E, GPa	25 °C		500 °C		900 °C	
				μ	CTF	μ	CTF	μ	CTF
Nextel 312	62Al ₂ O ₃ -24SiO ₂ -14B ₂ O ₃	11 ↓	150	0.59±0.10	4 000±1455	0.68±0.09	220±80	0.74±0.13	160±50
Nextel 312 HT	62Al ₂ O ₃ -24SiO ₂ -14B ₂ O ₃		150	0.53±0.05	3 400± 750	0.66±0.12	120±60	0.76±0.13	100±10
Nextel 440	70Al ₂ O ₃ -28SiO ₂ -2B ₂ O ₃		190	0.49±0.09	7 350±2950	0.65±0.13	8700±3250	0.66±0.11	3200±800
Nextel 440 HT	70Al ₂ O ₃ -28SiO ₂ -2B ₂ O ₃		↓	0.54±0.07	6 200±1550	0.80±0.08	6500±1030	0.64±0.10	280±60
Nextel 550	73Al ₂ O ₃ -27SiO ₂	10.5 ↓	↓	0.54±0.08	9 230±2500	0.36±0.05	7500±1500	0.73±0.26	3000±1000
Nextel 550 HT	73Al ₂ O ₃ -27SiO ₂		↓	0.52±0.03	4 300±1600	0.61±0.10	4800±1000	0.41±0.06	5000±1500
Nextel 610	Al ₂ O ₃	10.5	366	0.51±0.04	2 930± 900	0.28±0.07	5450±2500	0.32±0.03	3600± 600
Tyranno	50Si 30C 170 3Ti	11	180	0.17±0.03	17 700±5000	0.34±0.14	3100±500	0.62±0.15	1250± 500
HPZ	57Si 28N 10C 50	12.6	176	0.69±0.06	2 070± 400	0.59±0.13	2140±600	0.63±0.04	2000± 350

Notes:

-Tests conducted for ≈ 6000 fiber bundle in room air, 1 in./sec sliding velocity, 270 g load for up to 2 hr.

-HT designates fibers which have been heat treated (exposed) in air at 1700 °F for 12 hr.

-Uncertainties represent data scatter for at least three repeat tests for each condition.

TABLE IV.—FIBER TENSILE STRENGTH AT TEST TEMPERATURES^a

Fiber material	Composition, wt%	Diameter, μm	E, GPa	Tensile strength, MPa		
				25 °C	500 °C	900 °C
Nextel 312	62Al ₂ O ₃ -24SiO ₂ -14B ₂ O ₃	11	150	1700	1400	750
Nextel 312 HT	62Al ₂ O ₃ -24SiO ₂ -14B ₂ O ₃	↓	150	1250	1029	551
Nextel 440	70Al ₂ O ₃ -28SiO ₂ -2B ₂ O ₃		190	2000	1750	1500
Nextel 440 HT	70Al ₂ O ₃ -28SiO ₂ -2B ₂ O ₃		↓	1500	1300	1125
Nextel 550	73Al ₂ O ₃ -27SiO ₂			2201	1964	1761
Nextel 550 HT	73Al ₂ O ₃ -27SiO ₂	↓	↓	2201	1964	1761
Nextel 610	Al ₂ O ₃	10.5	366	2235	2032	2032
Tyranno	50Si 30C 17O 3Ti	11	180	3000	2200	1500
HPZ	57Si 28N 10C 5O	12.6	176	1625	1523	1456

^aData taken from manufactures' information literature.

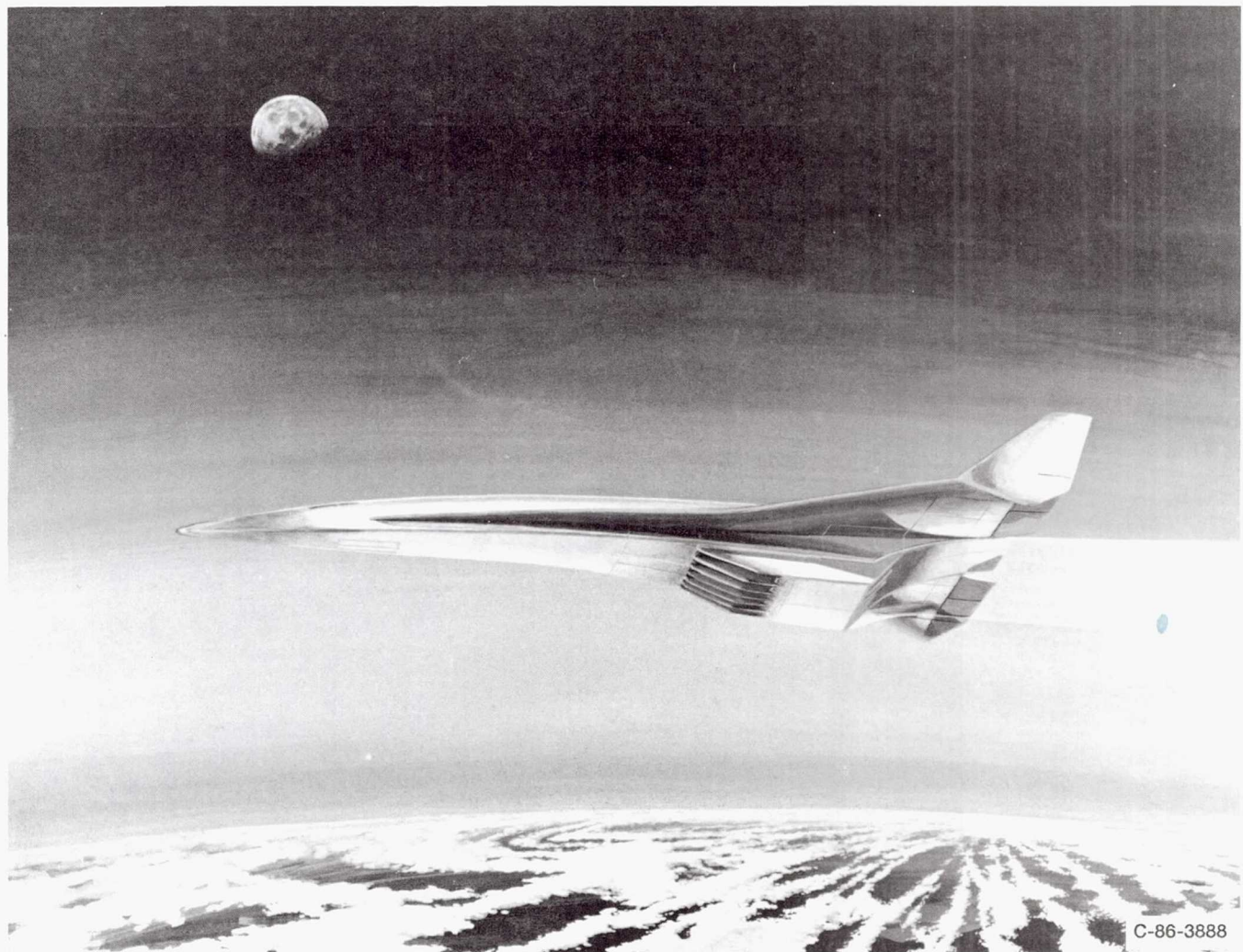


Figure 1.—Artist's conception of hypersonic flight vehicle (NASP).

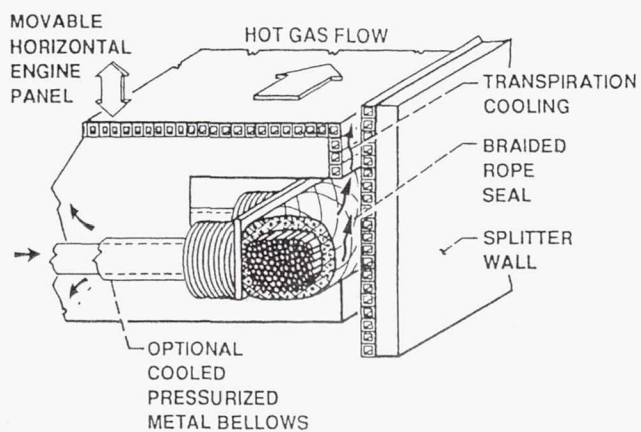


Figure 2.—Cross section of proposed engine seal.

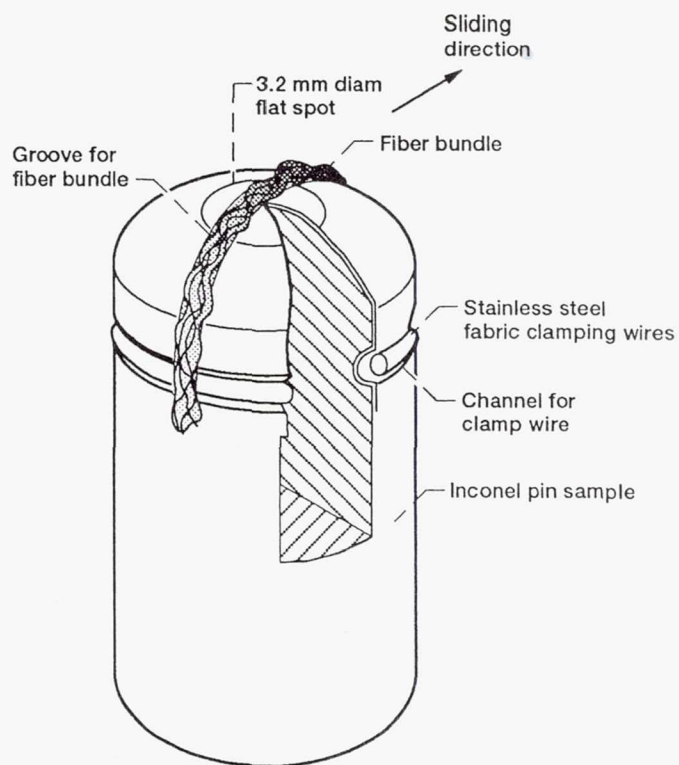


Figure 3.—Pin test specimen.



Figure 4.—SEM photomicrograph of fiber-pin specimen prior to testing. Sliding direction is from left to right.

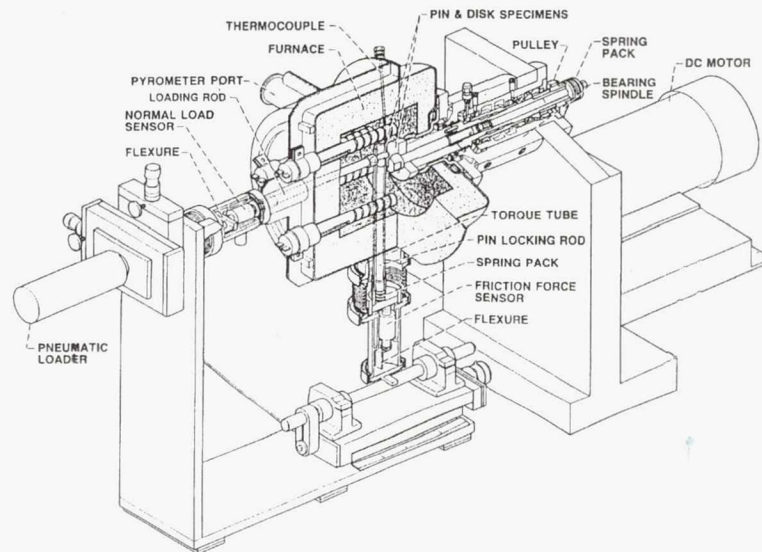


Figure 5.—High-temperature pin on disk tribometer.

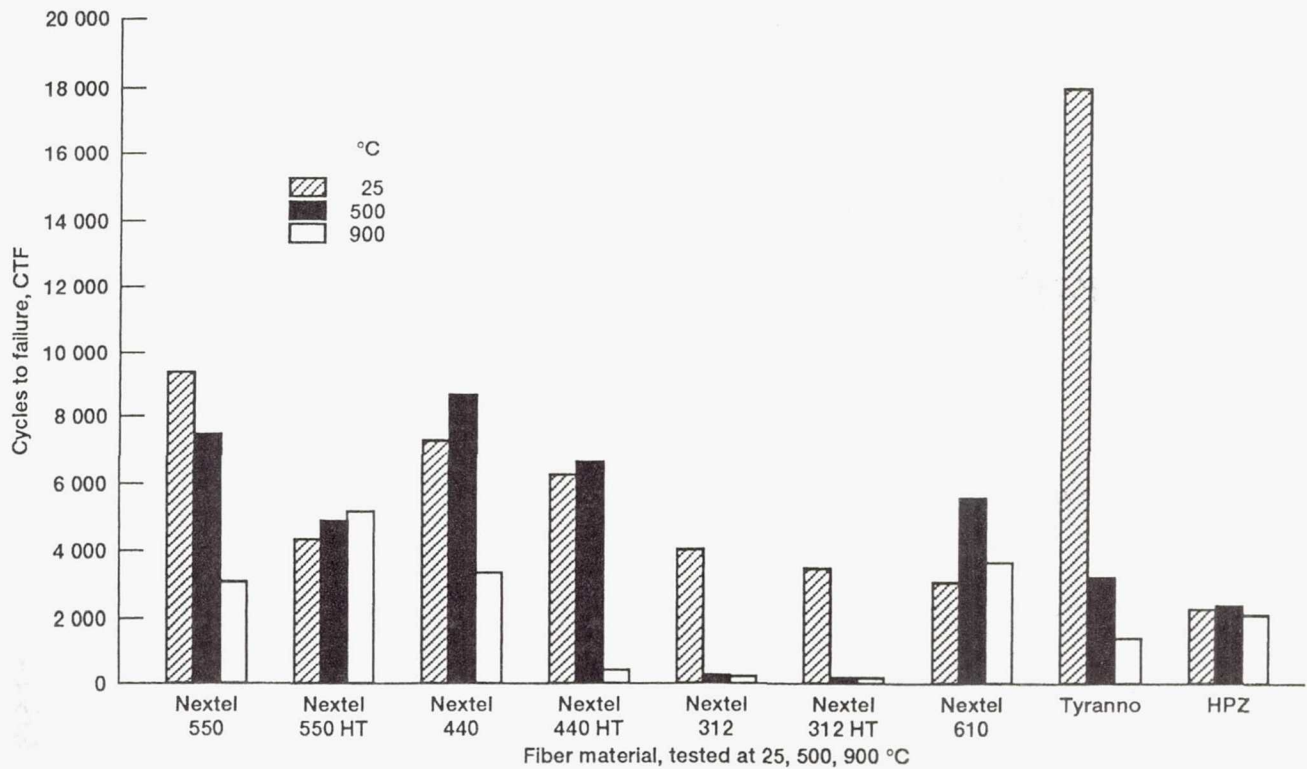


Figure 6.—Durability, CTF, for the fibers sliding against Inconel 718 counterface at 25, 500 and 900 °C. Test load 2.6N, velocity 0.025 m/s. Each data value represents an average of at least 3 repeat tests.

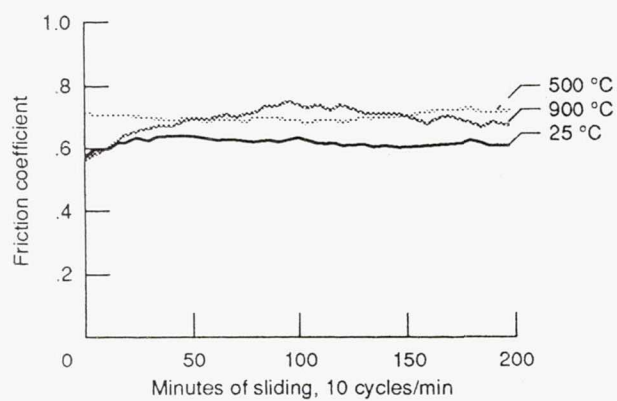


Figure 7.—Friction coefficient versus sliding time for Nextel 440. Test conditions: 0.27 kg (2.65 N) load, Inconel 718 counterface disk, air atmosphere, 2.5 cm/sec sliding velocity.



Figure 8.—Nextel 440 fiber-pin specimen after sliding for 24 hr at 25 °C. Very few fibers are broken indicating good durability.



Figure 9.—Nextel 440 HT fiber-pin specimens after testing at 900 °C. Virtually all of the fibers were broken during the test indicating low durability.

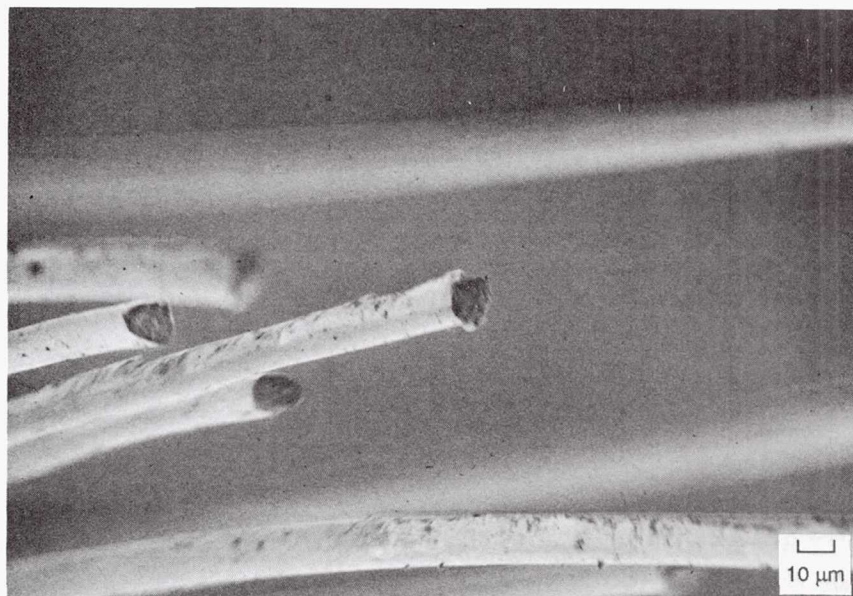


Figure 10.—SEM photomicrograph: Fractured fiber surfaces after sliding at 900 °C.

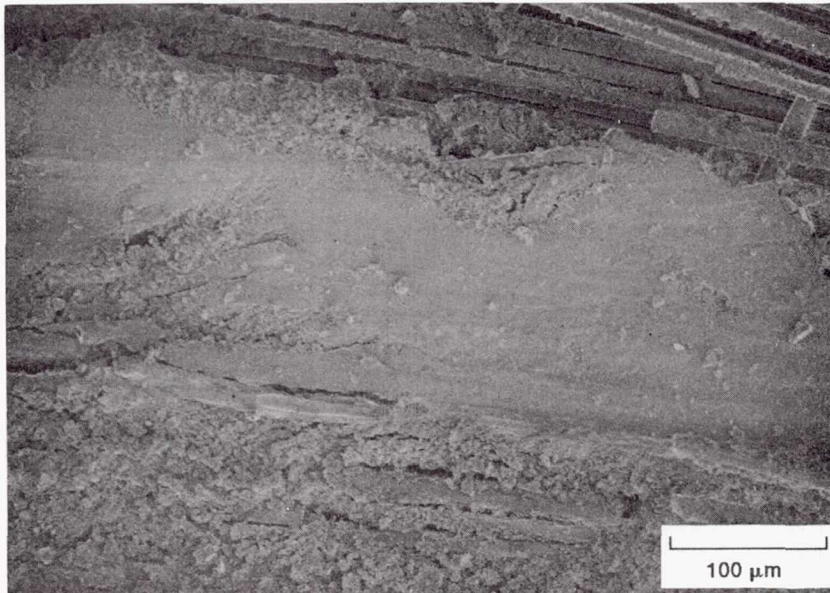


Figure 11.—Wear debris deposit on fiber surface of Tyranno specimen after sliding at 900 °C.

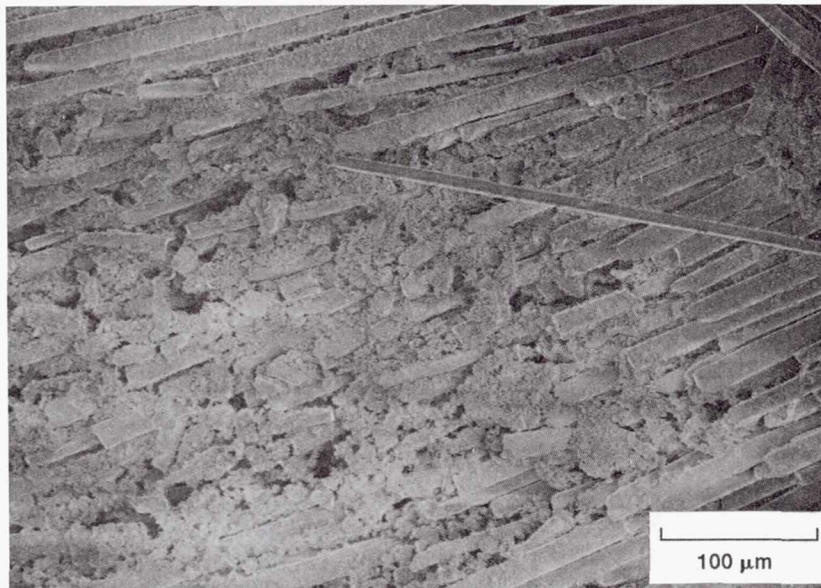


Figure 12.—Wear debris deposit on surface of HPZ fibers after sliding at 900 °C.

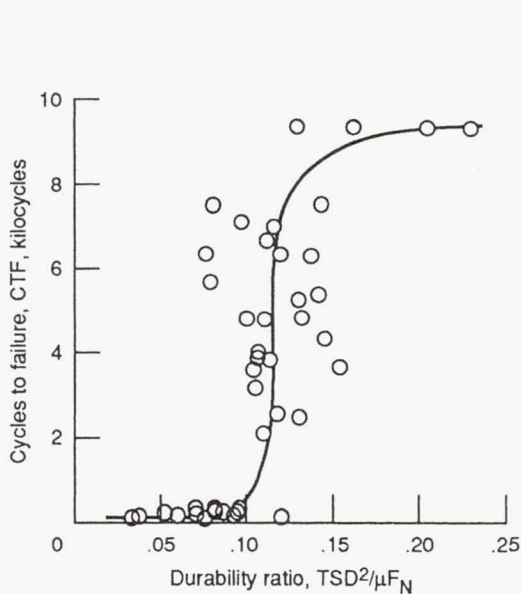


Figure 13.—CTF, cycles to failure, versus durability ratio, $TSD^2/\mu F_N$, resembles step function with discontinuity or transition occurring between 0.075 and 0.15.

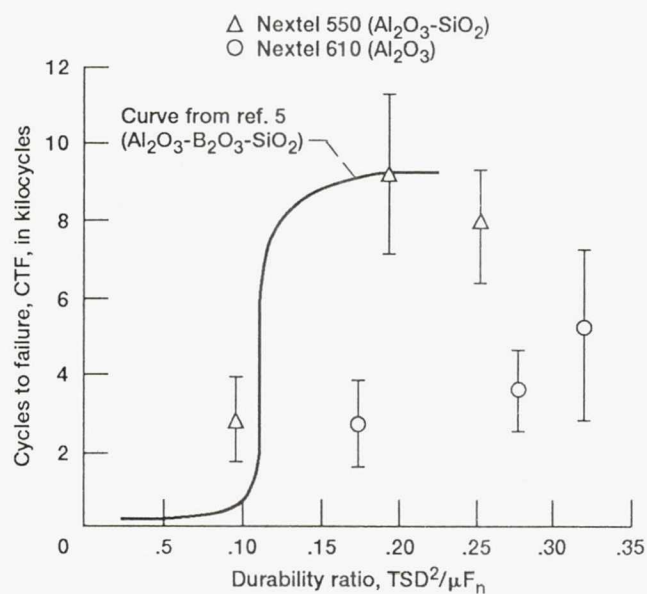


Figure 14.—Durability data for Nextel 550 and Nextel 610 fibers plotted versus dimensionless durability ratio. Nextel 550 data shows good agreement with data curve generated in reference 5 for $Al_2O_3-B_2O_3-SiO_2$ fibers (Nextel 312 and Nextel 440). Nextel 610 data shows poor agreement which may be due to high stiffness of the Al_2O_3 fibers. Each data point shown represents the average of at least three repeat tests. Error bars represent data scatter.

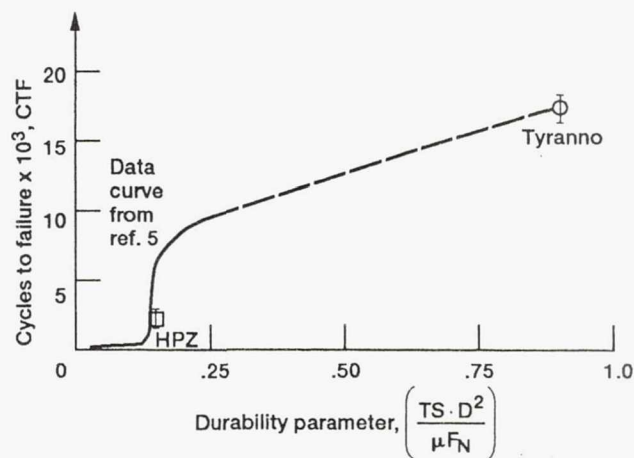


Figure 15.—Fiber durability (CTF) vs. non-dimensional durability parameter which represents fiber strength in tension to sliding friction forces. Data for HPZ and Tyranno shown from tests at 25 °C. Error bars represent data scatter from repeat tests. Curve (solid portion) generated in ref. 5. Results show a relation between fiber wear and mechanical properties.

REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE February 1992	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Relative Sliding Durability of Candidate High Temperature Fiber Seal Materials			5. FUNDING NUMBERS WU-505-63-1A 763-22-28	
6. AUTHOR(S) Christopher DellaCorte and Bruce M. Steinetz				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-7236	
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-105806	
11. SUPPLEMENTARY NOTES Christopher DellaCorte and Bruce M. Steinetz, Lewis Research Center, Cleveland, Ohio. Responsible person, Christopher DellaCorte, (216) 433-6056.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 23			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) <p>This paper reviews and compares the relative sliding durability behavior of six candidate ceramic fibers for high temperature sliding seal applications which has been previously reported by the authors in several separate publications as part of an ongoing research program. Pin on disk tests were used to evaluate potential seal materials by sliding a tow or bundle of the candidate ceramic fiber against a superalloy test disk. Tests were conducted in air under a 2.65 N load, at a sliding velocity of 0.025 m/sec and at temperatures from 25 to 900 °C. Friction was measured during the tests and fiber wear, indicated by the extent of fibers broken in the tow or bundle, was measured at the end of each test. For most of the fibers, friction and wear increase with test temperature. The relative fiber durability ranking correlates with tensile strength indicating that tensile data, which is more readily available than sliding durability data, may be useful in predicting fiber wear behavior under various conditions. A dimensional analysis of the wear data shows that the fiber durability is related to a dimensionless durability ratio which represents the ratio of the fiber strength to the fiber stresses imposed by sliding. The analysis is applicable to fibers with similar diameters and elastic moduli. Based upon the results of the research program, three fiber candidates are recommended for further study as potential seal materials. They are a silicon based complex carbide-oxide fiber, an alumina-boria-silica and an aluminosilicate fiber.</p>				
14. SUBJECT TERMS Ceramics; Fiber; Seals; Friction; Wear; High temperatures			15. NUMBER OF PAGES 20	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	